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LUMINANCE CONTRAST REQUIREMENTS FOR COLORED SYMBOLS IN HELMET-MOUNTED DISPLAYS

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13. ABSTRACT *(Maximum 200 words)*

Previously, we presented an experiment in which we defined minimum, but not sufficient, luminance contrast ratios for color recognition and legibility for helmet-mounted display (HMD) use. In that experiment, observers made a subjective judgment of their ability to recognize a color by stopping the incremental increase in contrast ratio of a static display. For some target color/background combinations, there were extremely high error rates and in these cases sufficient contrast ratios were not achieved. In the present experiment, we randomly presented one of three target colors on one of five backgrounds. The contrast ratio of the target on the background ranged from 1.025:1 up to 1.3:1 in steps of 0.025 . As before, we found that observers could accurately identify the target colors at very low contrast ratios. In addition, we defined the range in which color recognition and legibility became sufficient (³ 95% correct). In a second experiment we investigated how well observers did when more than one color appeared in the symbology at one time. This allowed observers to compare target colors against each other on the five backgrounds. We discuss our results in terms of luminance contrast ratio requirements for both color recognition as well as legibility in HMDs.

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LUMINANCE CONTRAST REQUIREMENTS FOR COLORED SYMBOLS IN HELMET-MOUNTED DISPLAYS

INTRODUCTION

The use of colored symbology in a helmet-mounted display (HMD) has the potential to give the warfighter a significant combat advantage compared to monochrome symbology (2). Unfortunately, it is not as technically easy to employ colored symbology as monochrome symbology in an HMD. Monochrome symbology can be displayed using only one phosphor and relatively high levels of luminance output can be achieved. The use of colored symbology is more complex, and may require tradeoffs in resolution and luminance (3). Since the potential use of colored HMD symbology is still in the developmental stages, it is important to establish the minimum and optimal parameters for its employment. Specific parameters that need to be addressed include luminance, contrast, and hue.

In a previous experiment, we presented results from a study aimed at determining the minimum, or sufficient, luminance-contrast ratio for three symbology colors presented against five backgrounds (1). The method employed in that experiment was to slowly increase the luminance contrast of the symbology until the observer said they could identify the color of the symbology. With this method we found an unacceptably high error rate for some symbology colors on some backgrounds. In these cases, observers sometimes stopped the increase in symbology luminance when they thought the color could be identified, and then responded incorrectly. Thus, we were able to determine minimum, but not sufficient, luminance contrast ratios for the use of colored symbology in an HMD. The current studies were undertaken to define the minimum luminance contrast ratio of colored symbology required for warfighter use in an HMD. Because errors in symbology would be unacceptable for warfighter in a flying and fighting environment, the minimally sufficient luminance contrast ratio in the current study requires nearly perfect color recognition and legibility of colored symbology.

METHODS

Participants

Five observers participated in the two parts of the study; four of the five participated in both parts. They were recruited from personnel employed at Wright-Patterson AFB. All observers had normal or corrected to normal visual acuity and normal color vision.

Apparatus and Stimuli

There were two parts to this study. In each part, observers viewed a representative HMD symbology that served as the target for this study (Figure 1). This symbology format is representative of a target designator box that is currently in use and has been used in several other

studies (1,2). The target was displayed on a 21-inch CRT monitor (EDL Displays, Dayton OH) and viewed at a distance of three meters. The sizes of the individual parts and numeric characters were set so that the visual angles agreed with the fielded version of the symbology.

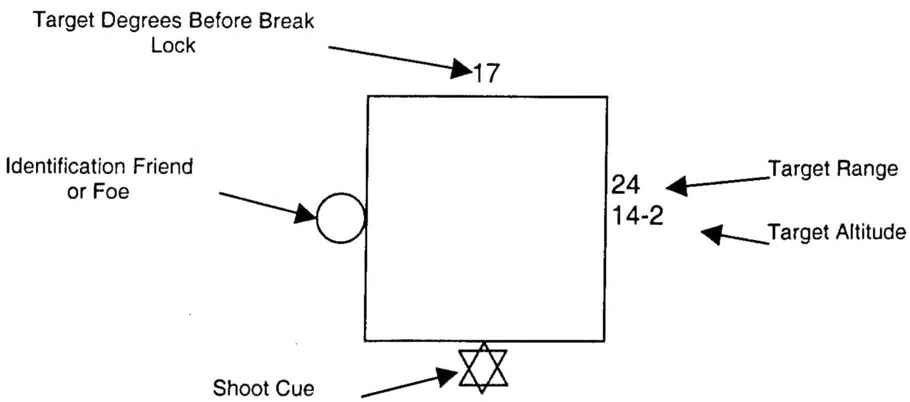

FIGURE 1. Target designator box symbology used in the experiment.

The target was presented in one or two of three possible colors: green, yellow, and red. The CIE 1976 chromaticity coordinates for these colors are shown in Table 1. These colors represent symbology colors that might be presented on a color HMD (1). The target was presented on one of five possible backgrounds that might be encountered during flight. Two of these backgrounds represent the sky during clear (blue sky) and overcast (hazy sky) conditions. The other three backgrounds (trees, sand, and brick) represent conditions that might be encountered when looking or flying toward the ground. The chromaticity coordinates of the five backgrounds are given in Table 1.

Each day before an experimental session was started, the color and luminance output of the monitor was measured and adjusted. A computer program was used to adjust the digital-to-analog converter (DAC) values so that every color was within a distance of 0.0015 on the CIE 1976 UCS chromaticity diagram and within 0.1 cd/m^2 in luminance of the intended values. This procedure minimized day-to-day variability in monitor output. The luminances of the background colors were always maintained at 25 cd/m^2. The luminance contrast ratios of the targets projected upon the backgrounds ranged from 1.025 to 1.300 in 0.025 steps. As an example, for a contrast ratio of 1.025, a target luminance of 25.625 cd/m^2 was shown with the background luminance of 25 cd/m^2 thus giving a contrast ratio of 1.025:1.

Experimental Procedure

Part One

All parts of the target (Figure 1) were presented as one color during the first part of this study. That is, during an individual trial, the entire symbology set was either green, yellow, or red. Targets were presented on backgrounds in each of the 12 possible steps at luminance contrast ratios ranging from 1.025:1 to 1.300:1. The target colors, background colors, and contrast ratios were randomized for each presentation. Each experimental session consisted of one presentation of each possible combination. Thus, with 3 target colors, 5 background colors, and 12 luminance contrast ratios, an observer made 180 responses per session. Each session lasted between 30 and 45 minutes and each of the five observers completed 10 sessions.

TABLE 1. CIE 1976 chromaticity coordinates for the colors used in the experiment.

Target Color	**u'**	**v'**
Green	0.115	0.5456
Yellow	0.2153	0.5477
Red	0.3713	0.529
Background Color	**u'**	**v'**
Blue Sky	0.1856	0.4416
Hazy Sky	0.2044	0.4812
Trees	0.1923	0.5136
Sand	0.2311	0.5088
Brick	0.2562	0.5064

All experimental sessions were conducted in a darkened room. Observers entered their responses on the numeric keypad of a keyboard. A small, dim light was used to illuminate the keyboard. The "enter" key was pressed to initiate a trial and a target/background/luminance contrast ratio combination was shown. After a few seconds of viewing, the observer pressed the "5" key and was asked to enter the target color - "4" for green, "5" for yellow, and "6" for red. The observer then pressed "enter" to record the response and was asked to enter the superior number of the targeting box symbology (target degrees before break lock) that was shown (see Figure 1). Pressing the "enter" key again recorded the numeric response and initiated another trial. The target remained on the screen while the color and numeric characters were being identified and entered. There was no time limit for a trial but observers were told to enter their responses as quickly as possible without sacrificing accuracy. If they were uncertain of the color or numeric character, observers were asked to randomly guess.

Part Two

In the second part of the experiment, the target was made up of two colors. The purpose was to determine if the simultaneous presentation of two colors would make color recognition significantly easier or more difficult. The identification friend or foe (IFF) symbol and the target degrees before break lock numerical characters were of one color and were termed the first component of the symbology. The remaining elements of the target (the second component) were always another color. The luminance contrast ratios of the two colors making up the target were always equal to each other. Based on the results from Part One, the number of step changes in luminance contrast ratio was reduced from 12 to 9. Luminance contrast ratios varied from 1.025:1 to 1.225:1 in 0.025 steps. The observer's task in Part 2 was to identify both of the colors making up the target.

The experimental session was similar to Part 1 with the exception that observers were asked to rate the confidence of their responses when identifying the color of the first and second components of the target. When observers were absolutely sure of the symbology color, they were asked to use the "7", "8," and "9" keys to enter responses for green, yellow, and red, respectively. The "4", "5," and "6" keys were used for "somewhat sure" responses and the "1", "2," and "3" keys were used for "guesses." The confidence rating did not have to be the same for the two colors. Further, observers did not have to identify the target degrees before break lock number as here we were only interested in color recognition.

RESULTS

Part One: Color Recognition

An analysis of variance (AVOVA) of background by target color was used to examine luminance contrast ratios for correct responses, and to examine percent correct values for color recognition. A within-subjects ANOVA of luminance contrast values for which observers correctly identified the symbology color yielded a significant effect of target color, $F(2,8) = 11.39$, $p < 0.005$. For these responses where the observer correctly identified the target color, the mean luminance contrast ratios were 1.176:1 for red, 1.178:1 for green, and 1.184:1 for yellow. Post hoc analyses using Tukey's HSD test at the 0.05 alpha level yielded significant differences of target color for red vs. yellow and green vs. yellow but not for red vs. green. The effect of background color for the correct responses was non-significant, $F(4,16) = 2.43$, $p > .05$.

The ANOVA of background by target color for the percent correct values also yielded a significant effect of target color, $F(2,8) = 8.97$, $p < 0.01$. The mean percent correct values were 89.7% for red, 86.9% for green, and 80.7% for yellow. Tukey's HSD test at the 0.05 alpha level yielded significant differences of target color only for red vs. yellow. The effect of background on percent correct values was not significant, $F(4,16) = 1.88$, $p > .05$.

One goal of this study was to identify the luminance contrast ratios required for nearly perfect color recognition. To make this determination, the responses from the five observers were averaged and the target color percent correct data were graphed as a function of contrast ratio for each target color on each background. The best fitting Weibull function was then determined (4). The form of the Weibull function is

$$P_c = 2/3(1 - e^{-(c/\alpha)^{\beta}}) + 1/3$$

where P_c is the percent correct, c is the contrast ratio, α is the threshold parameter, and β is the slope parameter. The 2/3 and 1/3 terms are adjustments for guessing since there were only three target colors. However, these terms were not included when evaluating the legibility data as there is no correction for guessing in this case.

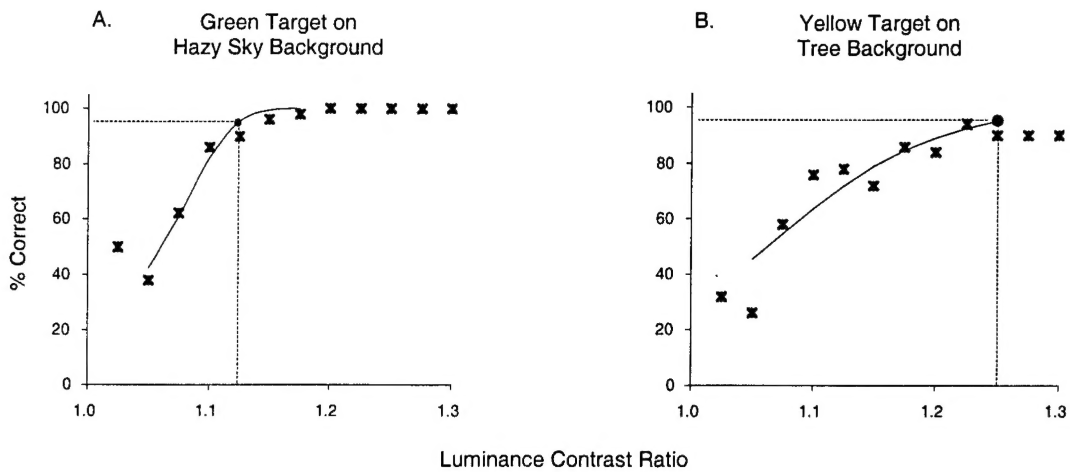

FIGURE 2. Average of five observer's target color percent correct values as a function of contrast ratio for (A) the green target on the hazy sky background and (B) the yellow target on the tree background. The solid lines show the best fitting Weibull function and the filled circles show the calculated point at the 95% correct response level.

Using the Weibull function, the luminance contrast ratios for 95% correct response values were calculated. Figure 2(A) shows an example of the data, Weibull function fit, and 95% correct value for the green target on the hazy sky background. The 95% correct point in Figure 2(A) corresponds to a contrast ratio of 1.12:1. This is a representative case and most of the other target/background combinations showed similar results. For the yellow target on the tree background, however, the overall percent correct value did not ever exceed 95% (Figure 2(B)). This low average was caused by the fact that one observer consistently identified the yellow target as green, even at high luminance contrast ratios. Although the average of the correct responses did not ever exceed the 95% level, it was possible to calculate the projected luminance contrast ratio for a 95% correct value by using the Weibull function.

In this case, a contrast ratio of 1.25:1 at the 95% correct value was obtained. Care must be used when interpreting this result. When the person who consistently identified the yellow target as green was excluded from the analysis, a luminance contrast ratio of 1.13:1 at the 95% correct value was obtained for the yellow target on the tree background.

Table 2 shows color recognition luminance contrast ratios at the 95% correct level for the three target colors on the five backgrounds. The color recognition luminance contrast ratio for the red target was less than for the other target colors on all backgrounds indicating that red was easiest to see. On two backgrounds (hazy sky and sand), the recognition of the yellow target was equivalent to the green target. Yellow was the most difficult to see on the remaining three backgrounds.

Part One: Character Legibility

An AVOVA of background by target color was used to examine luminance contrast ratios for correct responses and to examine percent correct values for character legibility. A within-subjects ANOVA of luminance contrast values for which observers correctly identified the target degrees before break lock number yielded a significant effect of background color, $F(4,16) = 6.03$, $p < 0.004$ and a non-significant effect of target color, $F(2,8) = 0.53$, $p > .05$. The mean luminance contrast ratios on the five backgrounds were 1.1953:1 (hazy sky), 1.1940:1 (blue sky), 1.1940:1 (brick), 1.1937:1 (sand), and 1.1921:1 (trees). Post hoc analyses using Tukey's HSD test at the 0.05 alpha level yielded significant differences of background for trees vs. hazy sky, trees vs. blue sky, and trees vs. brick.

An ANOVA of background by target color for the character legibility percent correct values also yielded a significant effect of background color, $F(4,16) = 5.68$, $p < 0.004$ and a non-significant effect of target color, $F(2,8) = 0.53$, $p > .05$. The mean percent correct values on the five backgrounds were 79.61% (trees), 78.33% (sand), 77.89% (blue sky), 77.78% (brick), and 77.33% (hazy sky). Tukey's HSD test at the 0.05 alpha level yielded significant differences for trees vs. hazy sky, trees vs. blue sky, and trees vs. brick.

As with the color recognition data, a Weibull function was fit to the percent correct vs. luminance contrast ratio data for the character legibility data. The calculated luminance contrast ratios for 95% correct values are shown in Table 2. These values are very similar to the color recognition values. At this high criterion (95%), red characters were identified at slightly lower luminance contrast ratios than were yellow or green characters in most cases. These results are consistent with the color recognition results.

Part One: Both Color Recognition and Character Legibility

The third column in Table 2 shows the luminance contrast ratios associated with 95% correct values when the criterion was for both color recognition and character legibility responses to be correct. These luminance contrast ratios are either equal to the highest value in the first two columns or slightly higher. The results indicate that there were few instances where color recognition was easy and character legibility was much more difficult or where legibility was easy and color recognition more difficult.

TABLE 2. Calculated luminance contrast ratios at the 95% correct response level for color recognition, character legibility and both color recognition and character legibility. *One observer who consistently identified the target color as green caused the higher values. The values in parentheses were obtained when this observer was removed from the analyses.

		Color Recognition	Character Legibility	Both
Background Color	Target Color	Luminance Contrast Ratio	Luminance Contrast Ratio	Luminance Contrast Ratio
Blue Sky	Green	1.09	1.13	1.13
Blue Sky	Yellow	1.13	1.12	1.14
Blue Sky	Red	1.07	1.10	1.10
Hazy Sky	Green	1.12	1.13	1.14
Hazy Sky	Yellow	1.12	1.12	1.14
Hazy Sky	Red	1.08	1.09	1.11
Trees	Green	1.10	1.12	1.12
Trees	Yellow	1.25 (1.13)*	1.12	1.23 (1.14)*
Trees	Red	1.08	1.12	1.12
Sand	Green	1.12	1.13	1.13
Sand	Yellow	1.12	1.11	1.12
Sand	Red	1.08	1.11	1.11
Brick	Green	1.12	1.12	1.15
Brick	Yellow	1.15	1.12	1.14
Brick	Red	1.09	1.11	1.11

Part 2: Color Recognition of the First Component of the Target

The first component of the target included the IFF symbol and the target degrees before break lock characters. During each trial, the first component of the stimulus was one color and the second component was a different color.

In Part 2 of this study, observers rated the confidence of their answers. There were three categories for the confidence ratings: 1) absolutely sure of the color, 2) somewhat sure of the color, and 3) guessing. The luminance contrast ratios for correct responses were analyzed by 1) including all correct responses regardless of the rating, 2) grouping correct responses for the absolutely and somewhat sure ratings together, and 3) including only the responses where the observer was absolutely sure of the color. The ANOVA of the luminance contrast values when observers correctly identified the color of the first component regardless of the confidence rating yielded a non-significant effect of target color, $F(2,8) = 2.04$, $p > .05$. The ANOVA for correct color identification when the absolutely and somewhat sure ratings were combined also showed a non-significant effect of target color, $F(2,8) = 1.57$, $p > .05$. Similarly, the ANOVA that included only the absolutely sure responses was non-significant, $F(2,8) = 0.51$, $p > .05$. The mean luminance contrast ratios for the correct responses, grouped as above, are

shown in Table 3. As can be seen, increases in observer confidence of correct responses are accompanied by increases in luminance contrast ratio.

TABLE 3. Mean luminance contrast ratios for correct responses for the first and second target components and for each target color. Data are grouped by the confidence rating of the observer's responses.

	Confidence Rating		
Target Color	**Any Rating**	**Absolutely and Somewhat Sure Combined**	**Absolutely Sure Only**
First Component	**Luminance Contrast Ratio**	**Luminance Contrast Ratio**	**Luminance Contrast Ratio**
Green	1.145	1.155	1.171
Yellow	1.144	1.157	1.173
Red	1.148	1.154	1.170
Second Component			
Green	1.147	1.157	1.173
Yellow	1.146	1.154	1.170
Red	1.143	1.155	1.173

An AVOVA of background by target color was used to examine percent correct values for color recognition. Confidence ratings were not used in this analysis. A within-subjects ANOVA of percent correct values for the first component yielded a non-significant effect of target color, $F(2,8) = 0.45$, $p > .05$. The overall mean percent correct values for three color target presentations of the first component were 83.76% for green, 82.38% for red, and 81.07% for yellow.

As in the first part of this study, the percent correct vs. luminance contrast ratio data for color recognition of the first component was graphed, a Weibull function fit, and the luminance contrast ratio at the 95% correct level was determined. Table 4 gives these luminance contrast ratios for each target color on each background. On each background, a higher luminance contrast ratio was obtained for yellow than for the other target colors. There is also an indication that the colors might be slightly harder to identify on the brick background than on the other backgrounds.

Part Two: Color Recognition of the Second Component of the Target

As was done for the analyses of the first component, the analyses of luminance contrast ratios for correct answers of the second component took observer confidence into account. The ANOVA of the luminance contrast values when observers correctly identified the color of the second component, regardless of the confidence rating, yielded a marginally significant effect of target color, $F(2,8) = 5.37$, $p < 0.04$. For these responses, the mean luminance contrast ratio was 1.143:1 for red, 1.146:1 for yellow, and 1.147:1 for green. Post hoc analyses using Tukey's HSD test at the 0.05 alpha level yielded a significant difference only for red vs. green. The ANOVA for correct color identification when the absolutely and somewhat sure ratings were combined yielded a non-significant effect of target color,

$F(2,8) = 1.76$, $p > .05$. The ANOVA that included only the absolutely sure responses was also non-significant, $F(2,8) = 0.70$, $p > .05$. The mean luminance contrast ratios for the correct responses are shown in Table 3.

A within-subjects ANOVA of percent correct values for the second component yielded a significant effect of target color, $F(2,8) = 21.67$, $p < 0.001$. The overall mean percent correct values for the three target color presentations of the second component were 90.16% for red, 81.73% for yellow, and 81.09% for green. Post hoc analyses using Tukey's HSD test at the 0.05 alpha level yielded significant differences of target color for red vs. yellow and red vs. green but not for yellow vs. green.

Table 4 shows the luminance contrast ratios at the 95% correct response level for the second component that were derived with the Weibull function. These values do not markedly differ from the first component values.

TABLE 4. Calculated luminance contrast ratios at the 95% correct response level for color recognition for the first and second components of the stimulus.

		First Component	Second Component
Background Color	Target Color	Luminance Contrast Ratio	Luminance Contrast Ratio
Blue Sky	Green	1.10	1.10
Blue Sky	Yellow	1.12	1.12
Blue Sky	Red	1.10	1.07
Hazy Sky	Green	1.11	1.10
Hazy Sky	Yellow	1.14	1.12
Hazy Sky	Red	1.09	1.08
Trees	Green	1.11	1.11
Trees	Yellow	1.17	1.10
Trees	Red	1.10	1.08
Sand	Green	1.12	1.13
Sand	Yellow	1.14	1.10
Sand	Red	1.09	1.09
Brick	Green	1.14	1.16
Brick	Yellow	1.15	1.11
Brick	Red	1.11	1.07

Part Two: Comparison of the First and Second Components of theTarget

Table 4 shows the luminance contrast ratio data for the two components of the target. Most values for the second component of the target are lower or the same as the values for the first component. A two-tailed paired t-test between the two components was statistically significant ($p < 0.02$). A

statistically significant difference was also obtained when comparing color recognition luminance contrast ratios from Part 1 to those for the first component of Part 2 (two-tailed paired t-test, $p < 0.005$). There was no significant difference between the Part 1 target and the second component of Part 2 target (two-tailed paired t-test, $p < 0.44$).

DISCUSSION

One of the primary goals of this study was to determine the minimum luminance contrast required for nearly perfect (95% correct) color recognition and character legibility for colored symbology. Excluding the yellow target/hazy sky background condition, the luminance contrast ratios at the 95% correct response level for color recognition ranged from 1.07 to 1.15 when the entire symbol set was one color (Table 2). The luminance contrast ratios for character legibility were similar and ranged from 1.09 to 1.13. Requiring the definition of a correct response to be a correct response for both color recognition and character legibility changed the results only slightly.

We hypothesized that luminance contrast ratios for color recognition might be reduced if the target contained more than one color. To study this, in Part 2 of this study we presented targets consisting of two colors. The luminance contrast ratios of the first component of the stimulus were slightly higher than those of the second component and the difference was statistically significant. From a practical point of view, however, the luminance contrast ratios for the first and second components of the target are essentially the same. Overall, having the target consist of two colors provided no enhancement in the ease of color recognition.

We previously reported minimum luminance contrast ratios obtained when observers made a subjective judgment of their ability to recognize a color by stopping the incremental increase in contrast ratio of a colored symbology (1). That study used the same three target colors on the same five backgrounds as the current study. The results for luminance contrast ratios for correct responses from our prior study are reproduced in Table 5. The minimally acceptable luminance contrast values from our current study (Table 2) are very similar to the values from our prior study (Table 5) even though the experimental methods differed. An important finding from our prior study was that observers often stopped the increase in luminance contrast ratio at a point where they thought they knew the symbology color and then wrongly identified the color. Thus, under certain conditions (e.g., a slow change in background color), some symbology colors might be difficult to identify correctly if luminance contrast is not above a critical minimum value.

TABLE 5. Data for color recognition and legibility from Havig et al, 2000. Reproduced by permission.

		Color Recognition	Character Legibility
Background Color	Target Color	Luminance Contrast Ratio	Luminance Contrast Ratio
Blue Sky	Green	1.16	1.16
Blue Sky	Yellow	1.17	1.16
Blue Sky	Red	1.12	1.13
Hazy Sky	Green	1.16	1.16
Hazy Sky	Yellow	1.17	1.17
Hazy Sky	Red	1.12	1.12
Trees	Green	1.14	1.14
Trees	Yellow	1.18	1.17
Trees	Red	1.12	1.13
Sand	Green	1.16	1.16
Sand	Yellow	1.17	1.17
Sand	Red	1.12	1.13
Brick	Green	1.18	1.17
Brick	Yellow	1.18	1.17
Brick	Red	1.12	1.13

It was shown that luminance contrast ratios varied with observers' confidence in their answers. As confidence increased, so did the associated luminance contrast ratios (see Table 3). When observers indicated that they were absolutely sure of their answers, they were correct 98% of the time and luminance contrast ratios were highest.

An observation made by most observers and one supported by the data was that the red symbology was much easier to identify that the green or yellow. This was especially evident when the second component of the target was red in Part 2 of the study. The percent correct values for this condition were 90.16% for red, 81.73% for yellow, and 81.09% for green and the difference between red vs. yellow and red vs. green was statistically significant. For users of HMDs with colored symbology, the knowledge that red will not be readily confused with green or yellow could be of critical significance.

Using colored symbology in HMDs may become a reality in the near future. I f colored symbology is used, it must not only be visible, but it must also be recognizable. The problem of color induction where the colors shift in appearance on some backgrounds has been addressed for CRT monitors (5) and must also be addressed for HMDs. By keeping the luminance contrast ratio of colored symbology above a specified minimum, the symbology will remain recognizable and useable.

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